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# Finite Element Prediction of Structural Failure of Space Payloads under Random Excitation using Different Solvers

**Abstract**— Space payloads are analyzed for their natural frequencies, and for survival under inertial loads and random excitation. In this paper, response of a typical space payload under Random Vibration is studied using Hypermesh/Optistruct and Nastran/Patran. Quadrilateral and Hexagonal elements used in the mesh to obtain higher accuracy and conservative results. Gaussian distribution with Kurtosis control 7 is used predict possible failure of the payload. Comparison of the results obtained by two solvers is made. A possible explanation to the difference in the results is also presented. The explanation helps to approximate results closer to theoretical values and the Gaussian distribution of higher order helps to predict failure of space payloads with higher confidence.

**Index Terms**— Random Vibration, Dynamic Simulation, Spacecraft payload.

## I. INTRODUCTION

The space components are required to be designed and analyzed with extreme care because they are irreparable and need to be maintenance-free. It has to withstand with loads caused due to transportation, lift-off loads, rocket-motor ignition overpressure, acoustics loads, pogo instability vibration loads etc. The Space components are usually analyzed and tested for natural frequencies to avoid resonance.[ 1] Random response analysis is also carried out so that effect of actual vibration excitation prevailing during launch can be simulated. The components are also tested for shock due to pyro-shocks and deployment of devices like solar panel, antenna etc. Components are subjected to vibration through their connection to satellite interface panel, while acoustics vibrations are directly transmitted to different surfaces of the components. Broadband random vibrations are produced due to engine functioning, structural response to the broadband acoustic loads and aerodynamic turbulent boundary layers. Failure modes under consideration in this work have been described in Vibration Analysis for Electronics Equipments by Steinberg .[2] Possible failure mechanisms displayed by components under these loads are described by Stephen H. Crandall & William D. Mark in Random Vibrations in Mechanical Systems. [3]

In the present study, a Crystal Oscillator assembly is analyzed for structural survivability using normal mode analysis, quasi static analysis and random analysis. A Crystal Oscillator generates electrical signals at particular frequency for Geo-stationary Satellite. Results are calculated for the same component with the help of two different CAE software Hypermesh/ Optistruct and Patran/ Nastran. FEM Model is prepared on the Hypermesh with the help of 2D shell elements and 3D Hex elements. Different types of cards required for random response analysis were also studied.

## II. RANDOM VIBRATION

Random Vibration is one of the most realistic kinds of excitation in which many frequencies present within a bandwidth act simultaneously at any time of excitation period. Evaluation of space sub-system under random vibration is carried out for simulation of the acoustic noise during launch, workmanship levels, pyro-shocks etc. The intensity of random vibration loads is given by Power Spectral Density (PSD) distribution over the excitation bandwidth. [4]

Methods to Carry out Random Vibration Analysis are:

- a) Direct Integration
- b) Mode Superposition

In case of direct Integration, the stiffness matrix is non-diagonal so there are numbers of equations required to be solved. If the structure is large, then it will require considerable amount of solver time and computer resources.

In modal superposition, using the orthogonality properties of the eigenvector, the stiffness matrix is made diagonal. Also, the damping matrix is assumed the combination of mass matrix and stiffness matrix for diagonalization of the matrix. With ortho-normality of the matrix, it is possible to reduce the number of equations required to be solved and hence, saves time. It can be done even on the considerably humble computer resources. [5]

Possible sources of error in Modal Superposition are:

1. A higher mode frequency is not approximated accurately by FEM model even if very fine mesh is used for meshing.
2. Assumption for diagonalization of damping matrix.
3. Modes extracted are not enough.

## III. CASE STUDY: CRYSTAL OSCILLATOR ASSEMBLY

The function of the crystal oscillator is to produce electrical signals of a particular frequency. The figure shows the OCXO Assembly which also incorporates the EPC and OCXO distribution box.

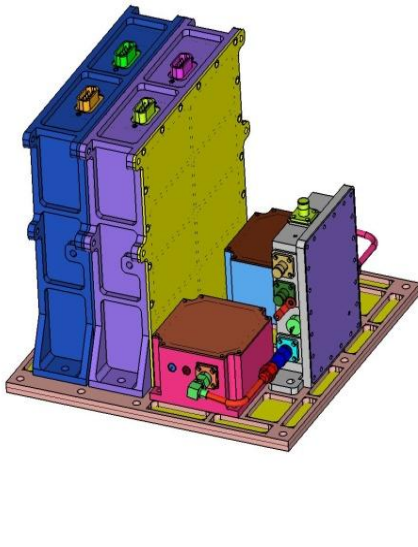


Figure 1: CAD Model of Crystal Oscillator

The material properties used for analysis are summarized in Table 1.

TABLE 1  
MATERIAL PROPERTIES USED IN ANALYSIS [6]

Component	Material	Young's Modulus (E) (GPa)	Poisson Ratio	Density (g/cm <sup>3</sup> )
Housing & Base Plate	Al. Alloy-6061 T6	70	0.33	2.7
PCB	FR4	25	0.12	1.9

Major assumptions taken for the analyses are:

- Linear Isotropic material properties are assumed under all loading conditions.
- Masses of connectors and feed through are assumed as lumped masses at appropriate locations.
- Mass of components over PCB is assumed to be uniformly distributed over the surface of PCB.
- Fasteners are not modeled in analysis. All interfaces fastening joints are simulated with 1-D rigid links.

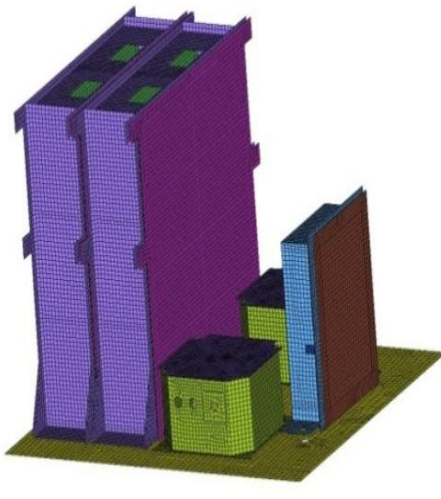


Figure 2: FEM Model of Crystal Oscillator

Random Vibration Loads - PSD Inputs are as follow:

TABLE II  
PARALLEL TO MOUNTING PLANE [7]

Frequency Range	PSD Inputs
20 to 100 Hz	+ 3dB/octave
100 to 700 Hz	0.1 g <sup>2</sup> /Hz
700 to 2000 Hz	-3 dB/octave

TABLE III  
PERPENDICULAR TO MOUNTING PLANE [7]

Frequency Range	PSD Inputs
20 to 100 Hz	+ 3dB/octave
100 to 700 Hz	0.28 g <sup>2</sup> /Hz
700 to 2000 Hz	-6 dB/octave

#### IV. ANALYSIS RESULTS

A component can fail due to resonance, high stresses, acceleration levels or displacement levels. At the internal resonance of the system components like relays and crystal oscillator due to acceleration, the components will not undergo catastrophic destruction but it will impair the performance of the package or stop the functioning of the system.

There are two kinds of mechanism involved in failure: (1) the acceleration goes beyond acceptable level for any instant of time. (2) It goes beyond the certain value for definite period of time. Both of the things can be determined by the Time domain analysis of the random vibration [2] [3].

Also, if the stress level increases beyond the yield strength of the material, it may go under structural deformation. It is a kind of mechanical failure which should be given importance because it leads to catastrophic destruction of the system. If two PCBs are mounted very close to each other, large relative displacements may cause them to strike each other, which might result into electronic failure or mechanical failure [2]. In this system, to avoid this only one PCB is mounted in each box.

Electrical Signals may go out of suitable range due to change in harness, resonance with oscillator, etc. It is also important because if this happens the functionality of the system is lost [2].

To assess any possible failure, analysis results are summarized in Table 4 and 5.

TABLE 2  
NORMAL MODE ANALYSIS RESULTS

Mode No.	Mode Shape	Frequency (Hz) Hypermesh Optistruct	Frequency (Hz) Patran Nastran
1	Bending Mode of EPC	213.6	204.1
2	Bending Mode of OCXO Distribution Box	289.2	286
3	Bending Mode of EPC PCB	359.8	345.8
4	Bending Mode of EPC PCB	386.6	377.1
5	Twisting Mode of EPC PCB	434.4	422.9

TABLE V  
RANDOM RESPONSE ANALYSIS RESULTS

	Hypermesh/ Optistruct	Patran/ Nastran
Maximum RMS Acceleration Tx	72.56	73.49
Maximum RMS Acceleration Ty	59.12	60.65
Maximum RMS Acceleration Tz	156.27	167.17
Maximum Von Miss Stress ( X- Direction)	16.18 MPa ( Control PCB)	36.3 MPa ( Control PCB)
Maximum Von Miss Stress ( Y- Direction)	36.52 MPa ( Interface between EPC and Base Plate)	41.3 MPa ( Interface between EPC and Base Plate)
Maximum Von Miss Stress ( Z- Direction)	32.8 MPa ( Control PCB )	69.4 MPa ( Control PCB )

Random Responses for X-directions are shown below:

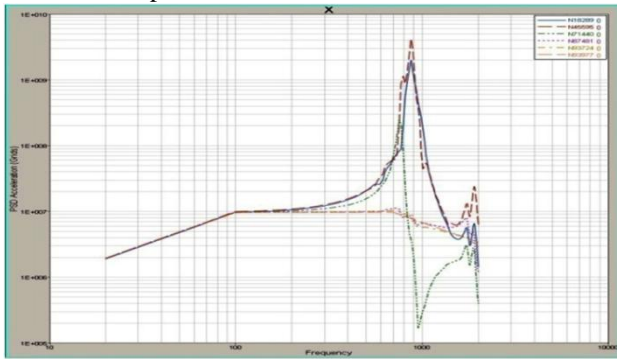


Figure 2: PSD Response for X-direction using Hypermesh/Optistruct

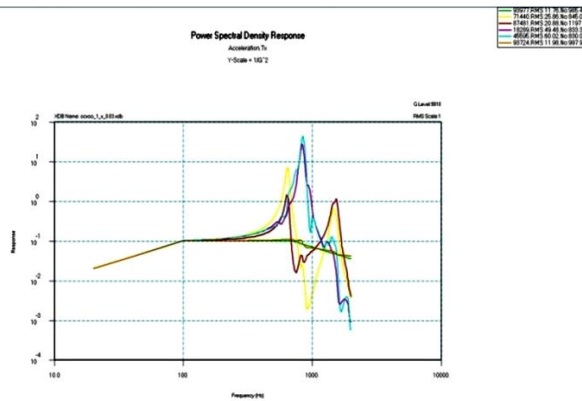


Figure 3: PSD Response for X-direction using Nastran

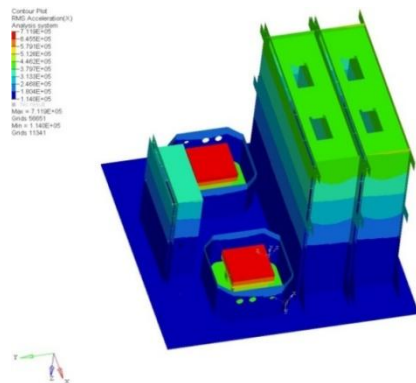


Figure No: 4: RMS Acceleration in X-Direction using Hypermesh/Optistruct

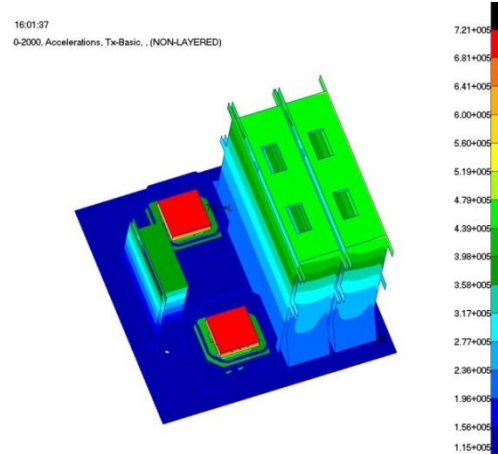


Figure No: 5: RMS Acceleration in X-Direction using Nastran

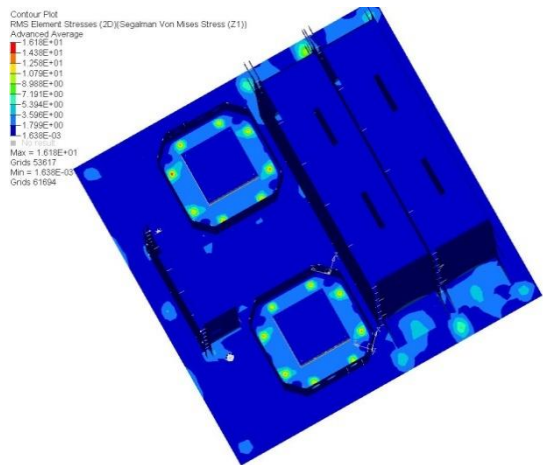


Figure No: 6: Von-Mises Stress Plot(X-Direction) using Hypermesh/Optistruct

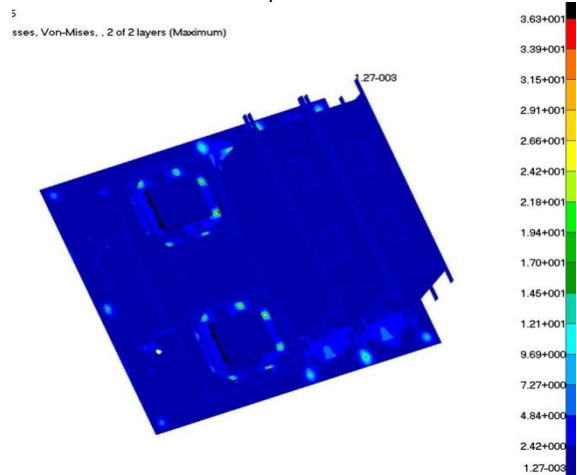


Figure No: 7: Von-Mises Stress Plot (X-direction) using Nastran

## V. EVALUATION AND INTERPRETATION OF RESULTS

### A. Normal Modes and Inertial Loads

The 1st modal frequency obtained is 204.1 Hz. For this typical payload requirement was to have frequency above 100 Hz. Hence the margin of safety is 104%

For static inertial load of 20g in X and Y -direction and 30g in Z- direction, results are summarized in table 6.

TABLE VI  
SYSTEM BEHAVIOR UNDER INERTIAL LOADING

Load/ Axis	Maximum Stress (MPa)	Yield Strength (MPa)	Margin of Safety
20g/ X	8.67 ( Control PCB )	413 [1]	46
20g/ Y	31.42 ( Interface between EPC and Base Plate )	276	7.9
30g/ Z	16.18 ( Interface between EPC and Base Plate )	276	16.25

Since margin of safety is positive in all cases, structural failure is not predicted due to resonance or under inertial loads.

#### B. Analysis of Random Vibration Response in Time Domain

It is important to note that different parameters are responsible for failure. In case of absence of such information, we have to go for RMS values of the quantities like acceleration and von-mises stress to check survival characteristics of the structure. RMS values gives some indication of random vibration response, but it is not a complete description of the random process. Gaussian distribution of excitation is assumed in general, which gives a certainty that peak response has a probability of 0.27% for crossing 3 times RMS value. But a Gaussian distribution assumption for complete description of the random vibration in time domain for space payloads may lead to inaccurate results. According to a study carried out by John van Baren, Gaussian distribution with kurtosis control of 7 more accurately represents the random process for space payloads.

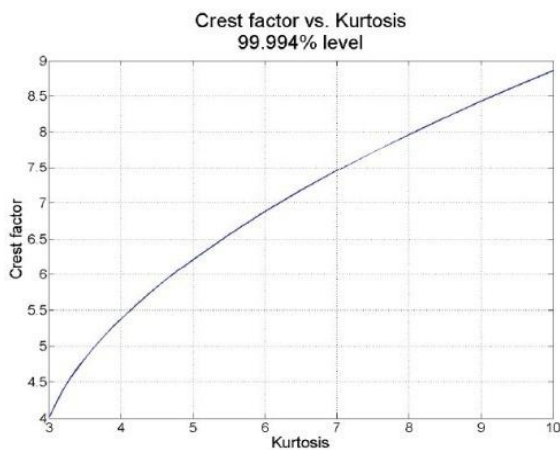


Figure No: 8: Crest Factor v/s Kurtosis Control

In the Gaussian Distribution Process of Kurtosis control of 7, Crest Factor is 7.5 which are further used for evaluation of results.

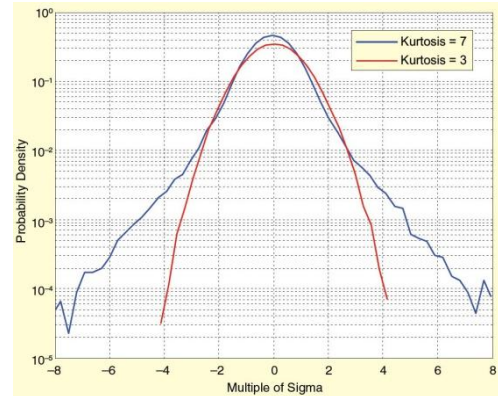


Figure 9: Comparison between Kurtosis Control 3 and 7 [8]

Field data goes beyond  $\pm 3$  times RMS value 1.50% of the time for space payloads, which is assumed 0.27% in case of Gaussian distribution. [8] Gaussian Distribution significantly reduces the time spent near the higher instantaneous value of acceleration So, It might lead to fatigue failure which is caused by the accelerations that go beyond  $\pm 2$  times the RMS value.

The system is subjected to random excitation for 120 seconds which means that peak acceleration occurs for about 7.2 milliseconds. The acceleration goes beyond  $\pm 3$  times the RMS value for 1.8 seconds which was assumed 0.324 seconds in Gaussian distribution process.

TABLE VII  
RESULTS SUMMARY

Factor Leading to Failure	Peak Value (for Kurtosis control 7 )	RMS Value
Acceleration	1253.775g	167.17g

The peak value of the acceleration occurs only for the instant of time at some nodal point. Hence, it doesn't lead to failure because of the inertial effects. RMS values of the acceleration and stress are well within the limit, so the system is safe under given input conditions.

#### C. Results obtained from Different Solvers

Different results are obtained from two solvers because modal superposition method is used for the solution of the dynamic equilibrium equation, and the normal modes obtained by two solvers are different.

#### VI. CONCLUSIONS

Crystal Oscillator is analyzed using two different solvers and the differences between simulation results are studied. Also, study of failure that might occur due to random vibration is also done in time domain and the structure is found safe for the same. Gaussian distribution with Kurtosis control 7 is used for the time domain study. A possible explanation for the difference in results from the two solvers is also presented. The explanation helps to approximate results closer to theoretical values and the Gaussian distribution of higher order helps to predict failure of space payloads with higher confidence.

#### ACKNOWLEDGMENT

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